Potentialities of optimal design methods and associated numerical tools for the development of new micro- and nanointelligent systems based on structural compliance - An example -

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Potentialities of optimal design methods and associated numerical tools for the development of new micro- and nano-intelligent systems based on structural compliance - An example -

C. Rotinat-Libersa, Y. Perrot and J.-P. Friconneau

***Abstract*—This paper deals with the interest and potential use of intelligent structures mainly based on compliant mechanisms (and optionally including smart materials), for the development of new micro- and nano-robotics devices. The state of the art in optimal design methods for the synthesis of intelligent compliant structures is briefly done. Then, we present the optimal method developed at C.E.A. L.I.S.T., called *FlexIn*, and its new and still in development functionalities, which will be illustrated by a few simple design examples. An opening will be given about the possibility to address the field of Nanorobotics, while adding functionalities to the optimal design method.**

***Index Terms*—Compliant structure, Intelligent structure, Smart materials, Topology optimization.**

I. Introduction

THE design and development of micro(nano)technology-based devices including sensors and actuators is in full expansion, whether it concerns miniaturization in microelectronics, or the broadening of research and applications in the biomedical field. For applications at this scale, measuring, characterization, or intervention instruments demand is growing.

Although numerous systems have been realized, they were rarely optimized. Moreover, specificity of the applications often implies the development of dedicated systems. When new needs deviate from the state of the art, the past experience about specific tools design isn't always sufficient to meet performance requirements. The number of aspects to be taken into account is a priori immense, because parameters influencing sensitively the design of such systems are several categories : structural (mechanics, electricity, chemistry), technological (nano-micro-macro technologies, development and assembly processes, connector technology), software linked (control, measurement), environmental (forces and physical interactions) and integration linked (dimension, nano-micro-macro physical interfaces). It is obvious that all these aspects have to be considered at the beginning of the design of a micro/nano dedicated system.

For all these reasons, the development of optimal design methods and associated numerical tools for micro/nano dedicated systems is an important research axis, which can bring all its relevance, if we consider the technological difficulties, the numerous prototyping stages (and the cost) necessary to : the realization of new systems of this type, the optimization of existing systems or that of their performances.

II. Compliant structures and optimal design : A state of the art

A. Advantages of monolithic flexible structures

Compliant mechanisms are single-body, elastic continua flexible structures, that deliver the desired motion by undergoing elastic deformation, as opposed to jointed rigid body motions of conventional mechanisms. When considering small scale systems (e.g. for microrobotics use [20]), there are many advantages of compliant mechanisms [38], among them: simplified manufacturing (easier integration), reduced assembly costs, reduced kinematical noise, no wear, no backlash (no clearance problems), and ability to accommodate unconventional actuation schemes (such as piezoelectric, electrostatic, and shape-memory alloys actuators) [41].

To illustrate this idea, let's consider the articulated micro-gripper that has been developed at I.E.M.N. (C.N.R.S.) (see Fig. 1) [51]. Even if functionality problems due to backlash and friction at the joints could be reduced by recent surface functionalizing techniques, the fabrication of the articulations by surface micromachining process, using e.g. a layered manufacturing approach, remains difficult (to obtain this

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gripper eight mask levels were used). Considering the use of compliant structures gives the opportunity to machine a micro-gripper mechanical structure in only one stage, with a less complex design and space, with a better fabrication success rate, and with better performances.

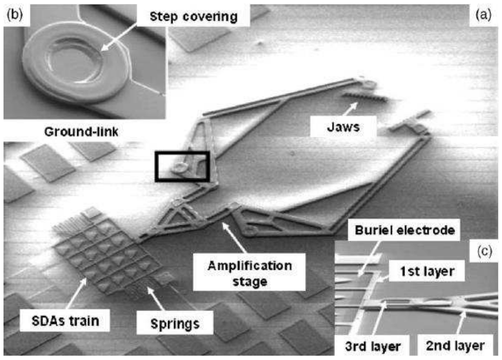


Fig. 1. Articulated polysilicon micro-gripper developed at I.E.M.N. (C.N.R.S.) [51], and actuated by 16 Scratch Drived Actuators.

B. A micro-robotic device example : compliant microgrippers

Compliant mechanisms have already been designed for use in many applications including product design, Micro Electro Mechanical Systems (MEMS), adaptive structures for vibration damping, tools for microsurgery and for cell manipulation, etc. Among these developments, compliant grippers are widely represented for various application fields, e.g. handling and manipulating micro-sized objects in MEMS applications, and in biotechnology. Many kinds of materials and actuators have been used to develop structures of micro-grippers. In the following, we describe some of the compliant grippers prototypes of the literature, and point out their specific functionalities (which were very rarely optimized).

A compliant meso-gripper (see Fig. 2) has been intuitive designed, developed, and jointed to a global macro-system, where the external actuator takes an important part of the space [40]. The dimensions of the arms have been optimized, and a superelastic NiTi material had to bee used, to maximize the displacement gripper tip, which was not so good at this scale using stainless steel (compared to articulated systems). Objects sizes of only 100 to 400 µm can be gripped, under a maximal 18 mN gripping force. This gripper allows gripping force measurement, despite a lack of integration and loss of space.

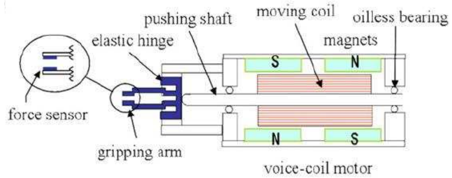


Fig. 2. Schematics of a superelastic NiTi flexure hinge microgripper (15.5 mm × 5.22 mm × 0.5 mm), actuated by 500 mN electromagnetic actuator, and including 44 µm-thick PVDF force sensor at the gripper tip [40].

A better integration concept of actuated compliant grippers, using e.g. PZT actuators, makes it is possible to realize smaller meso-grippers without degrading performances, and while keeping force sensing performances. It is the case in reference [2], where piezoelectric bender actuators generating a displacement of ± 250 µm and an actuation force of 0.07 N allow an effective stroke of the gripper of 1 mm with a 0.069 N gripping force. Nevertheless, this system (see Fig. 3) shows a non negligible encumbrance, as classical manual calibration stages are used to allow a 3 D.O.F. alignment to deal with large variation of the shapes and dimension of the microparts to be manipulated. A flexure hinge meso-gripper of close dimensions, actuated by a multi layer PZT stack actuator, and instrumented with semi-conductor strain gauges as force sensor, was designed with the objective to be used for characterization applications in microsurgery [50]. A remarkable gain in integrating actuation and sensing in a meso-gripper [56] (actuated by two piezoceramic parallel bimorphs, each having two D.O.F.), is based on the use of silicon technology force sensor, measuring forces from 1 to 230 mN with a resolution of 100 µN. The displacement of each finger is ±80 µm in x-y plane, and ±200 µm out of plane.

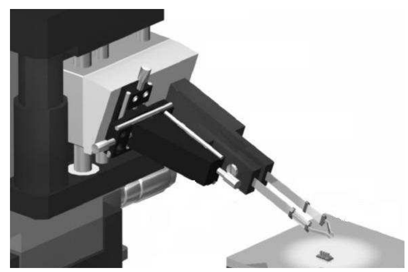


Fig. 3. Flexure hinge micro-gripper, actuated by two piezoelectric bender actuators, for clean environment working [2]. (arms : 103 mm × 62 mm × 70 mm).

Other smart materials have been tried as integrated actuators for compliant or monolithic [71] meso-grippers. Using the thermal-mechanical energy conversion, a SU-8 gripper actuated by a shape memory alloy (high work density material) has been realized (see Fig. 4), and allowed an opening stroke of 300 µm [58]. But such a gripper is difficult to manufacture, and has poor performances repeatability and reliability. A SU-8 microgripper has been realized in [18] using pneumatic power as actuation principle.

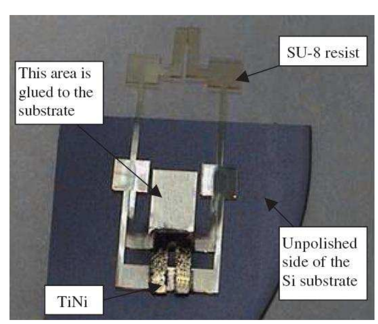


Fig. 4. Compliant SU-8 microgripper actuated by SMA thin film (17 mm × 6 mm × 145 µm) [58]

MEMS technologies are used to take advantage of thermal actuation, while reducing the scale of the gripping system.

Classical thermal bimorph actuators can be considered for monolithic design of compliant grippers [24]. Passive compliance (see Fig. 5a) can also bee used to compensate misalignment during insertion of a pin in a hole. The out of plane force during insertion is measured using capacitance changes of a comb structure attached in the base part of the gripper [43]. A very low voltage (2 V) is sufficient to open up to a 11 μm stroke a SU-8 gripper with thermal actuation (see Fig. 5b) [24]. Nevertheless, the thermal energy efficiency of such gripper is poor, and the one D.O.F. displacements of the tips obtained for grippers of such dimensions are rather small.

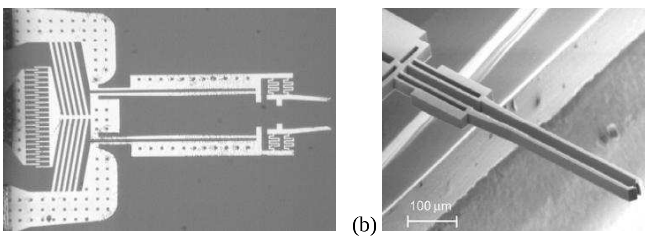
(a) (b)


Fig. 5. (a) SOI compliant microgripper (1,200 μm × 900 μm × 50 μm) for insertion applications [43]; (b) SU-8-based microgripper (thin metal resistor patterned at the bottom of the structure) to operate in physiological ionic solution [24]

Electrostatic micro actuators used for numerous MEMS applications, have been integrated for the design of a monolithically integrated gripper on a chip [21]. It is composed of (see Fig. 6) : 3 D.O.F. positioning stage, arms, supporting platforms (linear and torsional springs), bonding pads and conducting wires. It can be used to manipulate samples with dimensions from several micrometers to several hundred micrometers. But such a 2-D design needs large space, more especially when sensors should be added. For all such structural based compliance concepts, optimization methods may have great interest, when design oriented, and considering not only dimensions, but also a larger idea of topology, to find better solutions (and also adjust performances) than with intuition.

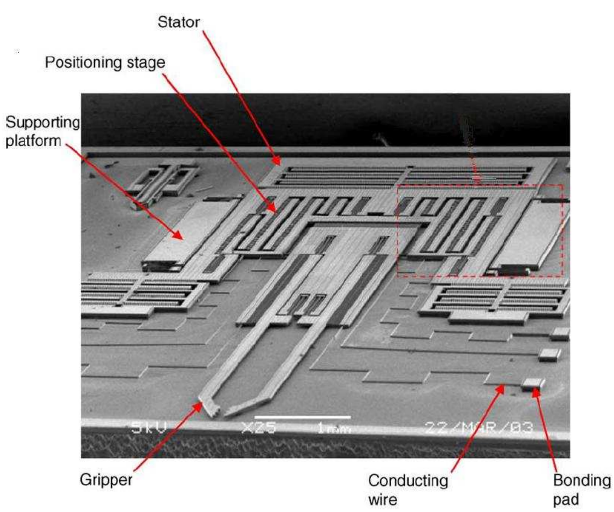


Fig. 6. Single crystal silicon monolithically integrated microgripper, actuated by two linear and one vertical comb actuators [21]. The displacement of the gripper is 5.9 μm under a 50 V driving voltage.

C. Topology optimization methods

Since a few years, there has been much researches and many developments investigated in the field of topology optimization, applied to the design of compliant mechanisms and smart structures [31]. The optimization works come from structures mechanics and dynamics, active damping, mechanical design and applied mathematics communities.

Two approaches known in the literature for the systematic synthesis of compliant mechanisms are the kinematics synthesis approach and the continuum synthesis approach. The first approach, known as flexure-based synthesis approach, represents and synthesizes compliant mechanisms using a rigid-body kinematics approach with flexible joints, and uses pseudo-rigid-body model ([36], [37], [66]). The continuum synthesis approach, based on the topology optimization method of continuum structures (Ananthasuresh *et al.* [8], [9], Nishiwaki *et al.* [53], Sigmund [62], Choi *et al.* [23]), focuses on the determination of the topology, shape and size. Generally, the optimization consider only one objective function, and uses, when a pseudo multi-criteria optimization is needed, an objective function composed of a weigh summation [54] of more simple criteria among : minimum weight [61], maximum stiffness (strain energy), flexibility (mutual strain energy) [53], mechanical advantage [63], etc. The methods based on this approach can be subdivided into, for example, the homogenization method and its variants [3], [4], [12], [13], [53], [62], [19], the level set method [5], [6], [7], [67], [68], [69], [70], the truss method [35], [29], [60], [62], [41], and the flexible building blocks method [14], [16], [34], [39]. A SOI micro-gripper structure (see Fig. 7) has been optimized for large jaws opening [54]. It is capable of handling and manipulating microparts with positional uncertainty (and the lack of sensory information) for 3-D structures snap-fit based microassembly experiments. Note that the distributed compliance and smooth deformation field of compliant mechanisms provide a viable means to achieve shape morphing in many systems [46], [47], such as flexible antenna reflectors.

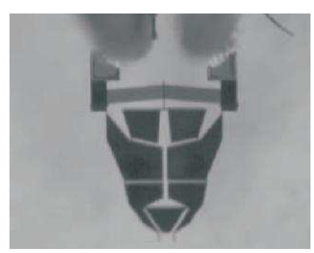


Fig. 7. Optimized compliant SOI microgripper with embedded thermal actuator (1,150 μm × 1,000 μm × 50 μm) [54]

Many optimization tools for design applications deals with compliant mechanisms coupled with smart materials. Numerous papers address the problem of designing coupling structures for piezoelectric actuator to act as a stroke amplifier. The objective functions are to maximize the geometric advantage, or to maximize the mechanical efficiency [30], [41], [42]. An optimized SU-8 micro-gripper actuated by an external PZT actuator to grasp micro size objects is presented in [23]. Moreover, the development of multi D.O.F. micro tools can allow to perform complex movements in small space. But when multiple actuators are involved, coupling effects in their movement becomes critical (especially the appearance of undesired movements) which makes the design task very complex. A systematic design method, such as topology optimization is a way to avoid such undesirable effects. A micro-tool structure, actuated by multiple piezoceramics, and that minimizes the effects of movement coupling has been optimized in [19]. Maximal mutual potential energy and minimal strain energy are other criteria considered in [28], to optimize the size of PZT pre-specified-located actuators simultaneously with the structure of a 3-D multifunctional compliant mechanisms, whereas in [1], the structure and the actuator are optimized successively.

Opposite to the methods, where the piezoelectric elements in the structure are predetermined, larger body of work related to optimization of smart structures deals with optimal location of actuators on a given structure. Here, the design variables are the coordinates and the size of the actuators [10]. Another general approach to optimally design smart structures is to simultaneously [48] or separately [1] optimize the compliant structure and the PZT actuator size. Only a few studies consider the optimization of the shape of monolithic PZT actuators [64].

Finally, in the context of intelligent structures design for new microrobotics devices, not only structural but also control optimization has to be taken into account. Thus, optimal design of number and position of actuators in actively controlled structures is considered in [44], whereas the size of the structure, and highly-distributed sensors and actuators location, are optimized using simultaneously robustness, controllability, and observability criteria, considering dynamic model [11], [45].

III. FlexIn: A COMPLIANT MECHANISMS STOCHASTIC DESIGN METHODOLOGY

In this section, we briefly present the flexible building blocks method developed at the French Atomic Energy Commission (CEA) in collaboration with the C.N.R.S.. This method has been implemented for planar mechanisms in a software called *FlexIn* (Flexible Innovation), developed with *Matlab*®. It uses an evolutionary algorithm approach for the optimal design of compliant mechanisms made of an assembly of basic building blocks chosen in a given library. A detailed description of the method can be found in [14], [16].

A. Compliant building blocks

A library of compliant elements is proposed in *FlexIn*. These elements are in limited number: the basis is composed of 36 blocks (see Fig. 8), which are composed of beams. They are sufficient to build a high variety of topologies, and it has been verified that they can describe many existing compliant structures of the literature. Moreover, the block feasibility related to fabrication process constraints can also be taken into account at this stage, which is not the case for classical beam-based optimization approach.

B. Principle of the method and design parameters

The purpose of *FlexIn* is to optimally design realistic compliant structures. The design method consists in searching for an optimal distribution of allowed building blocks, as well as for the optimal set of structural parameters and materials (see section D). The specification of planar compliant mechanism problem considers specific boundary conditions: fixed frame location, input (actuators), contacts and output (end effector). The location of fixed nodes, as well as the number, force and application point of internal and/or external actuators, can be considered as optimal design parameters. Another possibility deals with the location of internal and/or external contacts.

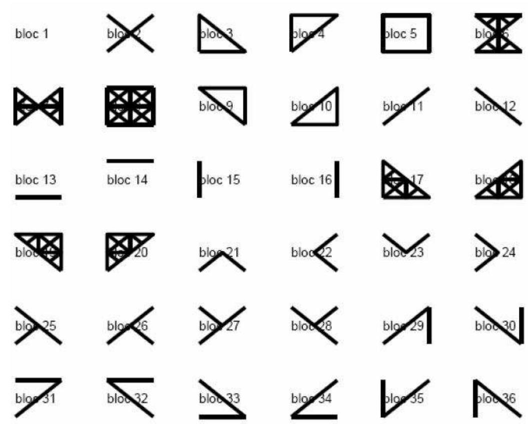


Fig. 8. Compliant building blocks library for two-dimensional compliant mechanisms synthesis using *FlexIn*

The topology optimization method (see Fig. 9), inspired from Deb *et al.* [27], uses a genetic algorithm approach, which allows true multicriteria optimization and the use of discrete variables. The algorithm is structured as follows:

- Discrete variable parameterization of compliant mechanisms considering conception requirements (mesh size, topology, material and thickness, boundary conditions),
- Evaluation of individuals (design criteria calculation),
- Stochastic operators for the optimization (modification of compliant mechanisms description).

C. Multi criteria genetic algorithm

Many fitness functions are available in *FlexIn*: displacement, rotation, and force at the output port, strain energy (SE), mutual strain energy (MSE), maximal stress (yield or fatigue strength), geometric advantage (GA), mechanical advantage (MA), mass, etc. Multi-degree of freedom compliant mechanisms designs can also be considered.

The optimization algorithm generates a set of pseudo-optimal solutions (see 2 in Fig. 9), in the case of multicriteria optimization problem, and obviously only one optimal solution for monocriterion optimization. The designer can choose, interpret and analyze the obtained structures that best suit his design problem (see 3 to 5 in Fig. 9). The Finite Element software *Cast3m*™ can be used for subsequent Finite Element solution, to analyze and validate the chosen design solution for criteria not considered during the optimization stage.

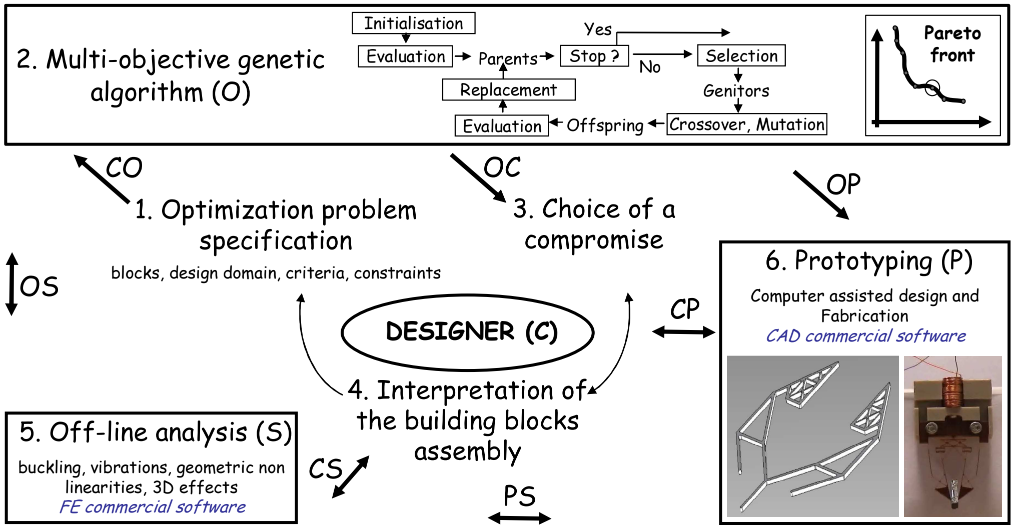


Fig. 9. FlexIn optimal design method of compliant structures: Flowchart of the algorithm (multicriteria optimization).

D. *Mechanical model of the blocks*

In *FlexIn*, it is assumed that the compliant mechanisms are undergoing structural deformation, mainly due to the bending of the beams. Thus, the following assumptions have been made: static state calculations, small perturbations, homogeneous and linear elastic model, Navier-Bernoulli beams with rectangular section. Structural parameters of each rectangular block are height, width and thickness. Material characteristics of each block are parameterized by Young's modulus, Poisson ratio, yield strength and density.

Firstly, the stiffness matrix of each block is calculated numerically, considering every combination of the discrete values allowed for the structural optimization variables. Then it is condensed, considering that non zero forces (i.e. inter-block connection forces) act only on the four corner nodes of the block. The calculation of the reduced stiffness matrix of each valued-block is done one time only at the beginning of the optimal design problem, before running the genetic algorithm, thus saving running time. Even if the resulting model is not exact (for twelve blocks of the library), it has been found that it has got few influence in the evaluation of the objective functions for most of the compliant structures generated, due to the type of block assemblies that generally occur. The condensed model of each block induces smaller numerical problem sizes for block assemblies, which is of great interest when using a genetic algorithm approach for multi-objective optimal design (here, numerous but simplified FE problems are being solved at each step).

Let's note that Kim *et al.* [39] have proposed an original building blocks method that considers only four bars building blocks, characterized by their instant center based kinematics. But the chosen strategy limits this method to topologic mono-objective optimization, and needs, according to the authors, subsequent size and geometry optimization to consider other performance criteria.

IV. Design examples of micro-grippers with *FlexIn*, using specific variables and criteria

In this section, we present through simple design examples, some of the synthesis possibilities with *FlexIn*. Note that a meso-gripper prototype (see fig. 9) has been realized at C.E.A. using this optimal design software (cf. section A).

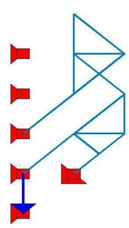
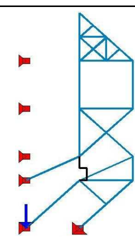
A. *Internal contacts*

Despite significant advances in development of systematic design techniques for compliant mechanisms, currently these mechanisms are not capable of performing certain kinematic tasks that rigid body mechanisms can readily perform. The design of compliant micro-devices can take advantage of non sliding contacts inside or outside the structure [49], that may enhance their functionality. To illustrate this idea, we tried to design [17] a flexible gripper based on the characteristics of the I.E.M.N. articulated micro-gripper [51], presented earlier in section II.A., and shown on Fig. 1. This study allowed also to understand what performances could be reached, comparing compliant design to articulated one.

Thus, it has been considered that the gripper should be symmetrical, and fixed to the global frame by two points. The same actuators were considered. Two criteria were optimized simultaneously, and were calculated for the gripping of a 0.4 mm diameter rigid object : the amplification ratio of displacement and the amplification ratio of force (jaw versus actuator). The specification of the optimization problems which have been run, are listed in the first rows of Table I. The first optimization considered the topology, the size of the blocks and the material+thickness as variables. The second one was also considering the fixed node position, and the location+backlash of the internal contact.

The obtained solutions were compliant grippers with mechanical static characteristics of comparable magnitude than for the articulated I.E.M.N. gripper (Table I, Results). It has been verified with a post-F.E.A. that the maximal Von Mises stress is far lower than the yield strength of the material, and that the buckling safety factor is acceptable. The results show that a compliant gripper (without internal contacts) can reach the displacement amplification level of the articulated one, only by reducing the force amplification rate. Indeed, some of the mechanical energy brought by the actuator is converted into strain energy in the structure. At the opposite, the use of unilateral contacts inside the structure induces a mechanical behavior with bifurcation, which may lead to a gain of output force without decreasing displacement performance (and vice versa).

TABLE I
PERFORMANCES COMPARISON OF THE ARTICULATED AND OPTIMAL COMPLIANT MICRO-GRIPPERS [17].
Material and thickness allowed during the optimization process were : 2, 4 and 6 µm for polysilicon, and 20, 40 and 60 µm for SU-8.

Characteristics	**Selected optimal compliant grippers**		**I.E.M.N. articulated gripper** [15] (theoretical values without friction)
Optimization problem specification			
Size (mm)	1.2 × 1.6	1.2 × 1.6	1.2 × 1.6
Actuation force (µN)	800	800	800
Optimized variables	topology, material & thickness, size	topology, material & thickness, size, fixed points, **internal contacts**	no optimization
Results			
Material & thickness	SU-8, 30 µm	SU-8, 30 µm	Polysilicon, 4.5 µm
Maximal jaw stroke (closure)	0.300 mm	0.300 mm	0.275 mm
Stroke amplification	5.1	7.7	5 (nearly constant along the stroke)
Force amplification	0.13 (for a 0.4 mm diameter object)	0.14 (for a 0.4 mm diameter object)	0.2 (nearly constant along the stroke)
Maximal gripping force (µN)	52 (for a 0.4 mm diameter object)	56 (for a 0.4 mm diameter object)	80 (nearly constant along the stroke)
Gripper half-topology model under *FlexIn*		 optimal backlash = -0.14 µm	---

To understand what the influence of the internal contact is, on the behavior of the compliant gripper, and what gain of performance may be obtained using such contacts, we analyzed the evolution of the gripping force for different size rigid objects. Fig. 10 allows the comparison of the gripping force between the following three grippers : a compliant gripper with internal contact, the same gripper without internal contact, and the same gripper with locked contact. It is shown that the internal contact joints the advantage of the compliant gripper without contact and that of the gripper with locked one, in the particular case where every object sizes imply that the contact always close. Indeed, the internal contact gripper allow to manipulate small size objects with a non negligible gripping force, while maintaining good gripping performances for larger objects (other bifurcation behaviors can appear with other topologies and other backlash size at the internal contacts, and can be found in [17].).

Nevertheless, for this gripper with internal contacts, of global size 1.2 mm × 1.6 mm (see Table I), the optimized value of the initial contact-backlash (0.14 µm), which governs the contact closure, may not be obtained with the fabrication process used (this machining condition had not been considered as a design constraint during the optimization).

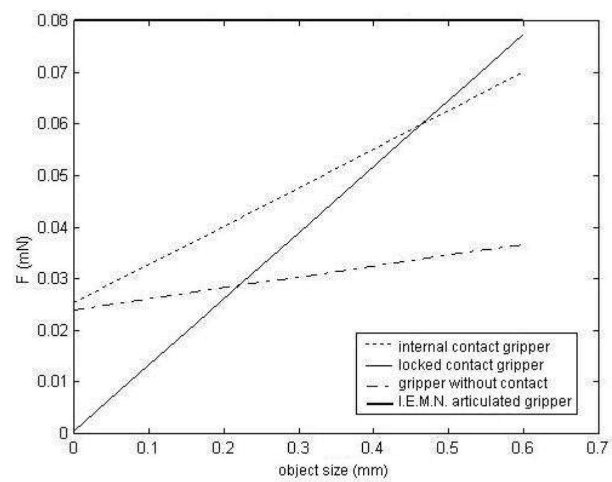


Fig. 10. Maximal gripping force for three different symmetric compliant grippers, compared to the nearly constant gripping force furnished by the I.E.M.N. articulated one, for different size rigid objects, and an actuation force of 0.4 mN (calculation realized on a half gripper).

B. *Maximum stress criterion*

Another criteria of importance for the design of compliant mechanisms is the maximal mechanical stress in the material. Indeed, plastic deformation, fatigue or over loading fracture should be avoided. This criteria has to be taken into account during optimization, to guarantee that the synthesized structures are viable. If not, the maximal stress is verified off-line on chosen optimal structures, which can be a loss of time for the design, when these structures appear not to be valid. We present in the following the method used in *FlexIn* to calculate the maximal stress, in accordance to the genetic algorithm optimization time constraints.

1) Maximal stress calculus for a block defined compliant structure [25], [26]: Let's consider a compliant structure generated by the genetic algorithm. For known actuation forces and boundary conditions, solving the linear system (1) leads to the displacements of all blocks four corner nodes $\underline{U_{global}}$. Then, the displacements of the four corner nodes are deduced for each block : $\underline{U_e}$.

$$\underline{F_{global}} = \underline{\underline{K_{global}}}\ \underline{U_{global}} \qquad (1)$$

For the library blocks number 2, 6 to 8, and 17 to 28, the internal nodes displacements have to be determined (for the other blocks, (3) can be directly used). Each block is defined by its stiffness matrix condensed at the four corner nodes $\underline{\underline{k_{cond}}}$. Equation (2) and $\underline{U_e}$ allow to find $\underline{F_e}$, the forces on the four corner nodes of the block.

$$\underline{F_e} = \underline{\underline{k_{cond}}}\,\underline{U_e} \qquad (2)$$

Then, to obtain the displacements of all the nodes of the block $\underline{U_{bloc}}$ (corner and internal nodes), it is necessary to calculate the total (non condensed) stiffness matrix of the block $\underline{\underline{k_{bloc}}}$. Nevertheless, the forces at all block nodes $\underline{F_{bloc}}$ is the concatenation of $\underline{F_e}$ for the four corner nodes and zeros for the internal nodes (simplifying hypothesis of *FlexIn*, see section III.D). Thus, $\underline{U_{bloc}}$ is determined solving (3) (by blocking the displacements of a chosen corner node). $\underline{U_{bloc}}$ gives the displacements $\underline{U_{ij}}$ of the two extremities of each beam (ij) of the block.

$$\underline{F_{bloc}} = \underline{\underline{k_{bloc}}}\,\underline{U_{bloc}} \qquad (3)$$

One can deduce the cohesion forces inside the beam. Firstly, forces $\underline{F_{ij}}$ at the extremities of the beam (ij) are calculated in the reference frame, using (4), where $\underline{\underline{k_{ij}}}$ is the stiffness matrix of the Navier-Bernoulli beam (of length *L*, of section area *S*, and of moment of inertia *I*), in the beam reference frame, and $\underline{\underline{P}}$ is the transportation matrix from the beam frame to the reference frame.

$$\underline{F_{ij}} = \underline{\underline{K_{ij}}}\,\underline{U_{ij}} = \underline{\underline{P}}^T\,\underline{\underline{k_{ij}}}\,\underline{\underline{P}}\ \underline{U_{ij}} \qquad (4)$$

Secondly, forces $\underline{f_{ij}}$ at the extremities of the beam (ij) are calculated in the reference frame of the beam, using (5).

$$\underline{f_{ij}} = \begin{pmatrix} N_{ij} & T_{ij} & M_{ij} & N_{ji} & T_{ji} & M_{ji} \end{pmatrix}^T = \underline{\underline{P}}\ \underline{F_{ij}} \qquad (5)$$

Then, the maximal stress in the beam (ij) is obtained considering the Von Mises stress for 1-D beam elements, given in (6). This stress is maximal at the node where the bending moment is maximal, i.e. at one of the beam extremities. Thus, for each block of the structure, a maximal local stress σ_v can be considered. Finally, σ_{max} the maximal mechanical stress of the structure can be deduced.

$$\sigma_v = \sqrt{\left(\frac{N_{ij}}{S}\right)^2 + \left(\frac{M_{ij} \times L/20}{I}\right)^2} \qquad (6)$$

2) Mechanical stress criterion considered during optimization: The calculus of the maximal stress in the structures, generated by the genetic algorithm during the optimization, allows to define a criterion that penalizes those which don't undergo elastic deformation. This criterion should allow to evaluate the viability of the structures and to compare them for the genetic selection stage. In our study, the objective is to minimize σ_{max}, which is equivalent to maximize (σ_{lim} - σ_{max}), but this first criterion do not warranty that $\sigma_{max} \leq \sigma_{lim}$) [25], [26] (Another criterion (7) has been proposed in reference [55], and implemented to automatically suppress non valid individuals during the evolution process, thus no more appearing on the Pareto front).

$$\begin{cases} 1/\sigma_{\max} & if\ \ \sigma_{\max} < \sigma_{\lim} \\ \sigma_{\lim} - \sigma_{\max} & if\ \ \sigma_{\lim} \leq \sigma_{\max} \end{cases} \qquad (7)$$

3) Design example: We present here the design of a compliant gripper to show the gain of taking into account the maximal stress during the optimization process. The schedule of conditions is : encumbrance of 12 mm × 15 mm, actuation force of 0.7 N, polysilicon material, jaw displacement to reach is 3 mm (closure). The optimization variables are : topology, size, material+thickness (two different polysilicon material). The objective functions to be maximized simultaneously during the optimization are the displacement and force amplification rates. Another multi-criteria optimization will be considered with a third criterion : minimize the maximal stress.

The optimization without stress criterion gives the Pareto front of Fig. 11. The optimization with the added stress criterion gives the Pareto fronts of Fig. 12. The comparison between the two displacement-force Pareto front show that, taking into account the stress criterion during the optimization reduces the *a priori* attainable force and displacement performances of the generated structures. Table II gives solution examples chosen respectively on the Pareto fronts of Fig. 11 and 12. It shows that the synthesized solutions, considering the stress criteria during optimization, are valid.

C. Monolithic active PZT-gripper

One type of smart material actuator widely used in compliant intelligent structures is piezoceramic PZT actuators (see section II). Such actuators are light devices, which offer the advantages of a high energy density and a high output force, when compared to conventional actuation principles at small scales. Even though one limitation of piezoelectric actuators is that they can only produce about 0.1% strain, resulting in a restricted range of motion, an optimal design via *FlexIn* has to be considered, for mechanical amplification capabilities of truss-like structures. Moreover, piezoelectric materials can be manufactured into desired shapes, which makes realistic the realization of piezoelectric monolithic compliant mechanisms.

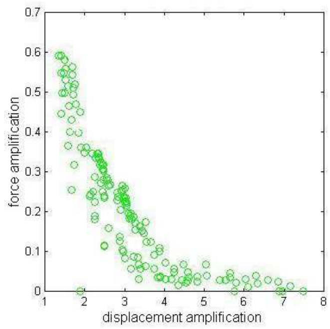


Fig. 11. Pareto front obtained for the optimization without the stress criterion.

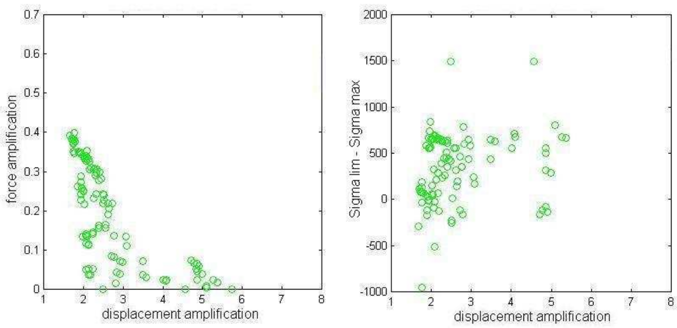
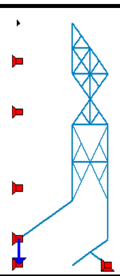
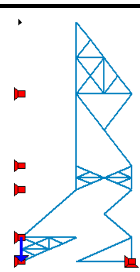


Fig. 12. Pareto front obtained for the optimization with the stress criterion. The structures which have a negative stress criterion are not valid, because $\sigma_{max} \geq \sigma_{lim}$ (i.e. Von Mises stress greater than yield stress)

TABLE II
COMPARISON BETWEEN SELECTED OPTIMAL COMPLIANT GRIPPERS OBTAINED WITHOUT AND WITH CONSIDERATION OF THE MAXIMAL STRESS BASED CRITERION [25], [26].
Materials allowed during the optimization process were two different polysilicon with a thickness between 0.6 and 1 mm.

Optimization	without maximal stress criterion	with maximal stress criterion
Gripper half-topology model under *FlexIn*		
Optimal material and thickness	E=192,000 MPa (σ_{lim} =1,200 MPa) 0.6 mm	E=165,000 MPa (σ_{lim} =1,500 MPa) 0.8 mm
Stroke amplification	2.4	2.6
Force amplification	0.27 (4 mm diameter object)	0.28 (4 mm diameter object)
Maximal σ_v (gripper closed)	2,040 MPa (off-line FE analysis)	1,045 MPa
Design validity	NO	YES

Thus, the *FlexIn* method has been adapted to consider a more global systematic design approach, where topology optimization of the structure, as well as that of integrated piezoelectric actuators (i.e. location, topology and size), is used to design monolithic PZT compliant smart mechanisms [34]. For that purpose, an active block library has been created for actuation (Fig. 13), and the piezoelectric constitutive equations of PZT material integrated, to furnish the FE model for active and passive use of the PZT blocks. Actually, active blocks are those which are bonded with electrodes, exploiting the piezoelectric actuator effect, while passive blocks are made in the same piezoelectric material but without electrodes.

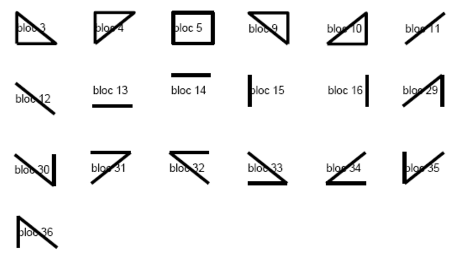


Fig. 13. Two-dimensional PZT active compliant building blocks library of *FlexIn*

To demonstrate the interest of this new potential of *FlexIn*, the synthesis of a two-dimensional symmetric monolithic PZT compliant microgripper has been realized. Location and topology of both passive and active blocks were optimized, whereas thickness was taken constant in the whole structure. Output stroke and force maximizations were the objective functions to optimize simultaneously.

Two optimization problems have been solved, using respectively a library made of PZT beam actuators, as often met in the literature, and the active blocks library. The criteria of the optimal solutions obtained are plotted on Fig. 14.

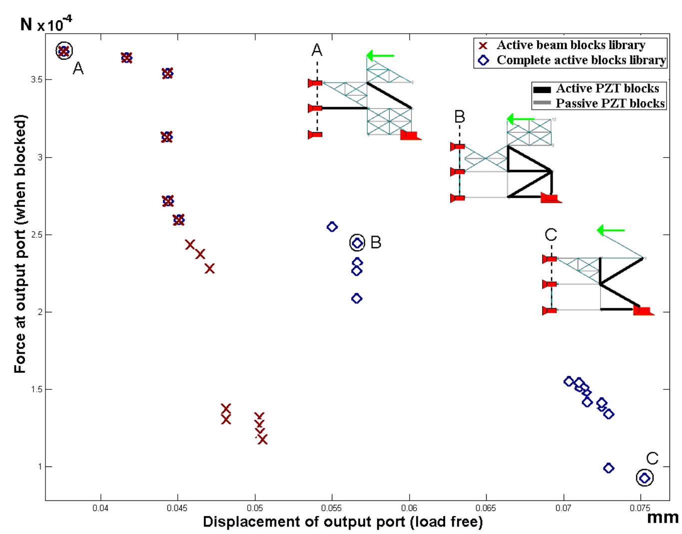


Fig. 14. Pareto graph of piezoelectric compliant microgrippers synthesized using FlexIn (half gripper dimensions are 5 mm × 9 mm, the thickness is 10 µm, PZT material is PIC 151 from PI Piezo Ceramic Technology [57], the input voltage is 150 V). A, B and C are selected half-topologies (markers are boundary conditions, arrow is the output displacement optimized).

As forecasted, the passive PZT blocks act like stroke amplifiers, whereas the active PZT blocks can furnish multiple coupled degrees of freedom, thus generating more complex movements with a lower encumbrance. To illustrate, microgripper B (see Fig. 14) allows a gripping force about 0.25 mN and a stroke between jaws of 113.07 µm (orthogonal stroke is 2.97 µm; in-plane jaw rotation is 0.52º). One perspective envisaged is to take advantage of the direct piezoelectric effect, to consider as well force sensor integration inside monolithic structures.

V. Potential developments of *FlexIn* for the design of micro- and nano-robotic devices

Other design criteria are being considered by the authors for their integration into *FlexIn* : minimization of the output port rotation (e.g., for the design of parallel jaws grippers) and minimization of perturbation displacements along a desired output d.o.f. [59], [55]; optimal location of sensors, for measurement purposes and the design of characterization micro-tools [32]; optimal simultaneous location of actuators and sensors considering controllability and observability criteria for control purposes [33]; mechanical buckling load prevention [22]. Especially, the dynamic modeling of the flexible structure is now considered (structural mass and damping matrices).

But to obtain an efficient and versatile optimal design tool, some other developments of *FlexIn* should be considered in the future. These can be classified into many topics : extension of the method and of the associated numerical tool (3-D displacement modeling of the planar structures, and finite element model for the synthesis of 3-D compliant structures); new optimization criteria (encumbrance criterion to design more compact devices), new physical models (micro scale mechanical properties of the materials for the design of micro- and nano-devices, use of other smart materials, integration of micro- and nano-scale contact forces and environment modeling); technologically linked developments (integration of dedicated MEMS actuators or sensors, and consideration of meso-, micro- and nano-fabrication process constraints).

In a near future, these new developments could be used to design nano-robotic devices such as grippers but also legs, wings or aquatic propulsion members for robots [65]. For nanoscopic applications, Carbon Nano Tubes could also be considered as elementary flexible beams for the constitution of compliant blocks library, and the design of truss-like compliant structures, like grippers. Another nanoscale innovative elementary cell, for such designs, could be based on proteins assembly [52].

VI. Conclusion

In this paper, we have presented a state of the art on compliant mechanisms in microrobotics, and the topology optimization methods still in development for the design of these specific devices.

A new method suitable for optimal topology synthesis of compliant mechanisms, called *FlexIn*, has been presented. It considers a compliant mechanism as an assembly of compliant building blocks, using structural material as well as smart material (PZT), so that actuators can really be integrated in the structure. The method automatically generates optimal designs of compliant structures, for a specified schedule of conditions. The designer can choose a design among a set of pseudo-optimal solutions of various topologies. He may have to investigate it further, off-line. Indeed, some specific aspects linked to micro-scale models, and technological aspects are not implemented yet in *FlexIn* optimization software.

The choice of the criteria to consider for the optimization depend on the application, and has to be as large as possible. Moreover, the performance testing on prototypes is necessary to verify the simplifications assumed in the different models included, as well as the real performances of the generated structures.

Considering new research and potential applications, addressing the field of the nanorobotics should be possible, while adding functionalities to the optimal design method. This will be possible only if the different scientific communities (microrobotics and microtechnologies communities, for example) share and capitalize their competences and knowledge, to make the development of generic numerical tool for the optimal synthesis of micro/nano robotic devices efficient and meeting the needs.

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